

# “Hidden” Seyfert 2 Galaxies and the X-ray Background

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## ABSTRACT

Obscured active galactic nuclei, which are classified optically as type 2 (narrow-line) Seyfert galaxies in the local universe, are by far the most promising candidates for the origin of the hard (2–10 keV) X-ray background radiation. However, optical follow-up observations of faint X-ray sources in deep *Chandra* images have revealed surprising numbers of apparently normal galaxies at modest redshift. Such objects represent  $\sim 40$ –60% of the sources classified in deep *Chandra* surveys, raising the possibility that the X-ray galaxy population has evolved with cosmic time. Alternatively, most of the faint X-ray galaxies in question are so distant that their angular diameters are comparable to the slit widths used in ground-based spectroscopic observations; thus, their nuclear spectral features may be overwhelmed (“hidden”) by host-galaxy light. To test this hypothesis, we have obtained integrated spectra of a sample of nearby, well-studied Seyfert 2 galaxies. The data, which accurately simulate observations of distant *Chandra* sources, demonstrate convincingly that the defining spectral signatures of Seyfert 2s *can* be hidden by light from their host galaxies. In fact, 60% of the observed objects would not be classified as Seyfert 2s on the basis of their integrated spectra, similar to the fraction of faint X-ray sources identified with “normal” galaxies. Thus, the numbers of narrow-line active galaxies in deep *Chandra* surveys (and perhaps all ground-based spectroscopic surveys of distant galaxies) are likely to have been underestimated.

*Subject headings:* galaxies: Seyfert — X-rays: diffuse background — X-rays: galaxies

## 1. Introduction

Identification of the classes of objects responsible for the cosmic X-ray background radiation (XRB) has been one of the fundamental pursuits of X-ray astronomy for the past several decades. It now appears that different populations produce the majority of the background in different X-ray energy bands. In the soft 0.5–2 keV range, active galactic nuclei (AGNs) with broad optical emission lines (i.e., Seyfert 1 galaxies and quasars) are the dominant contributors to the XRB (Schmidt et

al. 1998). These objects, however, have steep X-ray spectra and cannot explain the flat slope of the XRB spectrum at higher energies. Type 2 (narrow-line) Seyfert galaxies have thus emerged as the most promising candidates for the origin of the hard (2–10 keV) XRB. The soft X-ray fluxes of these objects are heavily absorbed by dense circumnuclear gas, presumably the same material that obscures their broad emission-line regions. Models (Madau, Ghisellini, & Fabian 1994; Comastri et al. 1995; Gilli, Salvati, & Hasinger 2001) and X-ray observations of nearby sources (Moran et al. 2001) have demonstrated that Seyfert 2 galaxies have both the space density and X-ray spectral properties necessary to account for the intensity and spectrum of the hard XRB.

The *Chandra X-ray Observatory*, which resolves the majority of the XRB in deep exposures, provides an opportunity to confirm the Seyfert 2 hypothesis directly. Surprisingly, however, follow-up optical observations of faint sources in the deepest *Chandra* images have revealed a significant population of apparently *normal* galaxies and far fewer Seyfert 2s than expected (e.g., Mushotzky et al. 2000; Barger et al. 2001a, 2001b, 2002; Hornschemeier et al. 2001). “Normal” galaxies represent  $\sim 40\text{--}60\%$  of the hard X-ray sources classified in deep surveys; many exhibit evidence of absorption in the X-ray band, but emission lines are very weak in their starlight-dominated optical spectra. The multiwavelength properties of the prototypical example of this class are described by Comastri et al. (2002a). The prevailing interpretation is that optically normal, X-ray-luminous galaxies are common at modest redshifts, perhaps reflecting a tendency for AGNs in the past to be more absorbed or have weaker ionizing continua than present-day Seyfert galaxies (Barger et al. 2001a). This hints at the possibility that the X-ray galaxy population has evolved with cosmic time.

Alternatively, we propose that the results of the deep *Chandra* surveys may be heavily influenced by the limitations of ground-based observing. In spectroscopic observations of nearby AGNs, light is collected through a small aperture centered on the nucleus, which excludes most of the starlight from the host galaxy. The faint sources that produce the hard XRB, in contrast, are very distant (the majority are at redshifts  $z \gtrsim 0.5$ ); thus, when they are observed, the entire galaxy (or a large fraction of it) falls within the spectrograph slit. (At  $z \approx 1$ , 10 kpc corresponds to  $\sim 1''.5$ .) Combined with the low spectral resolution that has been employed to date ( $\sim 12\text{--}20$  Å) and the modest signal-to-noise ratios frequently obtained (the optical counterparts are generally quite faint), the additional galaxy light (from stars and H II regions) could lead to the appearance that some distant *Chandra* sources are associated with normal galaxies rather than with Seyfert 2s.

To investigate this possibility we have obtained *integrated* spectra of nearby Seyfert 2 galaxies that are known to be absorbed X-ray sources. Our techniques simulate ground-based spectroscopic observations of distant X-ray galaxies, allowing us to evaluate whether the emission-line signatures of their activity can be overwhelmed (or “hidden”) in spectra of their integrated light. This project draws inspiration from a series of papers by Kennicutt (1992a, 1992b), who obtained integrated spectra of nearby galaxies of all types to assist “the classification of unresolved galaxies at large distances [and] the spectroscopic identification of extended sources detected in infrared, radio, and X-ray surveys” (Kennicutt 1992a). Our similarly motivated work focuses on the class of objects believed to be responsible for the hard X-ray background.

## 2. Observations and Analysis

The objects for this study are drawn from the distance-limited sample of Seyfert galaxies compiled by Ulvestad & Wilson (1989). There are 31 confirmed Seyfert 2s in the sample (Moran et al. 2000), almost all of which have been observed in the 1–10 keV band with the *ASCA* satellite (Moran et al. 2001). The Ulvestad & Wilson sample is ideal for this project for several reasons. First, because of its distance-limited nature, the sample is relatively unbiased. Second, the hard X-ray luminosities of the objects ( $\sim 10^{41}$ – $10^{43}$  ergs s $^{-1}$ ) are comparable to those of the “normal” galaxies in deep *Chandra* surveys (Barger et al. 2001a, 2001b; Hornschemeier et al. 2001). And finally, because all of the objects are located within  $\sim 60$  Mpc, most are close enough that we can isolate the emission from their nuclei yet distant enough (i.e., with sufficiently small angular diameters) that we can measure their integrated spectra with relative ease.

Our data were acquired with the 3-m Shane reflector at Lick Observatory over the course of three runs in August and November 2001 and February 2002. We employed 600 line mm $^{-1}$  dispersing elements on each arm of the Kast double spectrograph (Miller & Stone 1993), which provided coverage of the 3400–8100 Å range. For each galaxy, we obtained a 300 s exposure of the nucleus using a 2'' slit oriented at the parallactic angle (Filippenko 1982). The nuclear spectra represent 4''–5'' extractions along the slit and have a resolution of 5–6 Å (FWHM). Integrated spectra of each object were obtained by scanning an east-west slit across the galaxy in declination at a constant rate. Six scans were obtained for most galaxies, although a few of the brighter objects were scanned three to five times. For the scans, the width of the slit was increased to 6'' to improve our observing efficiency and to degrade the spectral resolution to 15–16 Å, comparable to that used in observations of faint *Chandra* sources (Barger et al. 2002; Hornschemeier et al. 2001). The angular distances of the scans (30''–120'' in declination) were dictated by the diameters of the galaxies in high-contrast images from the Digitized Sky Survey (DSS). Each scan had a duration of 600 s; combined with the slit width and scan distances, this yielded effective exposures of 30 s to 120 s per scan for each object’s integrated spectrum. These spectra include most of the light from each galaxy above the sky background (i.e.,  $\sim 35''$  to  $\sim 90''$  extractions).

We observed a total of 18 objects from our sample — all those at  $\delta > -23^\circ$  with projected angular sizes in right ascension (again, estimated from DSS images) of less than 2'. The latter restriction ensured that we would be able to perform accurate sky background subtraction with light that entered the slit near the two ends. The galaxies observed and some pertinent data are listed in Table 1. The optical and X-ray properties of the 13 objects we did not observe do not differ significantly.

## 3. Integrated Spectra of Seyfert 2 Galaxies

Recently published spectroscopic studies of faint *Chandra* sources are based mainly on data acquired with 8–10 m telescopes (Barger et al. 2002; Hornschemeier et al. 2001; Tozzi et al. 2001). In

most respects, the integrated spectra we have obtained accurately simulate observations of distant type 2 AGNs with these instruments. The scan distances and extractions employed for our sample include most of the light from the galaxies; they correspond to physical sizes of  $\sim 8\text{--}20$  kpc, similar to that which is typically included within a  $1.5\text{--}2''$  slit for a distant *Chandra* source. Our spectral resolution, as discussed above, is comparable to that used in *Chandra* source surveys. In addition, the effective exposure times associated with our scans are equivalent to  $1.5\text{--}2$  hr Keck exposures of objects  $\sim 7\text{--}8$  mag fainter, i.e., objects with visual magnitudes in the  $m \approx 20\text{--}22$  range. These roughly correspond to the Keck exposure times and magnitudes of distant *Chandra* sources that have been classified spectroscopically (Barger et al. 2001a, 2001b, 2002).

Examples of our results are displayed in Figure 1. The nuclear spectrum of NGC 262 (= Mrk 348; lower trace of Fig. 1a) bears all the characteristics of a type 2 Seyfert galaxy: strong [O II]  $\lambda 3727$ , [Ne III]  $\lambda 3869$ ,  $H\beta$   $\lambda 4861$ , [O III]  $\lambda\lambda 4959, 5007$ , [O I]  $\lambda 6300$ ,  $H\alpha$   $\lambda 6563$ , [N II]  $\lambda 6584$ , and [S II]  $\lambda\lambda 6717, 6731$  emission lines with high [O III]/ $H\beta$ , [O I]/ $H\alpha$ , [N II]/ $H\alpha$ , and [S II]/ $H\alpha$  flux ratios (Veilleux & Osterbrock 1987). These same features are clearly present in the integrated spectrum of the galaxy (upper trace of Fig. 1a), despite the presence of a significant amount of additional starlight. Thus, NGC 262 retains its Seyfert 2 classification in the integrated spectrum.

The spectra in Figures 1b–e tell a much different story. Once again, the nuclear spectra of these galaxies exhibit Seyfert 2 emission-line signatures. In the integrated spectra, however, the lines are far less prominent, and some are completely obliterated. The strongest spectral features are the Ca II  $\lambda\lambda 3934, 3968$ , G band ( $\lambda 4300$ ), Mg I  $b$   $\lambda 5176$ , and Na I D  $\lambda 5893$  stellar absorption lines typically observed in the spectra of normal early-type galaxies. Note that the [Ne III]  $\lambda 3869$  emission line, which has been used in *Chandra* source surveys to identify AGNs (Barger et al. 2001a, 2001b; Hornschemeier et al. 2001), is not visible in the integrated spectra. Thus, [Ne III] emission cannot be relied upon to indicate the presence of an active nucleus.

The data for NGC 3982 (Fig. 1f) provide an interesting third alternative. Although the emission lines in both the nuclear and integrated spectra of this object are strong, the line-flux ratios in the two differ dramatically. For example, in the nuclear spectrum, [N II]  $\lambda 6584/H\alpha \approx 1$  and [O III]  $\lambda 5007/H\beta \approx 16$ , which is typical for a Seyfert 2. In the integrated spectrum, however, [N II]/ $H\alpha = 0.37$  and [O III]/ $H\beta = 0.82$ , consistent with the values observed in H II regions (e.g., Veilleux & Osterbrock 1987). The [O I]/ $H\alpha$  and [S II]/ $H\alpha$  ratios also resemble those of H II regions. Given only the integrated spectrum of NGC 3982, we would classify it as a starburst galaxy rather than a type 2 Seyfert! We obtain a similar result for another object in our sample, NGC 1667. Thus, it is possible for the emission from star-forming regions to drown out an active nucleus in a galaxy, which sheds light on the nature of the “composite” starburst/Seyfert galaxies uncovered during optical surveys of *ROSAT* sources (Moran, Halpern, & Helfand 1996).

#### 4. Discussion and Conclusions

The last column of Table 1 indicates our assessment of the classifications of our galaxies based on their integrated spectra. While seven objects with strong lines in the nucleus remain as Seyfert 2s in the integrated spectra, 11 others (or  $\sim 60\%$ ) would *not* be classified as AGNs. This is comparable to the fraction of *Chandra* sources ( $\sim 40\text{--}60\%$ ) identified with “normal” galaxies in deep surveys (Barger et al. 2001a, 2001b, 2002; Hornschemeier et al. 2001). Among the normal-looking subset of our sample, nine objects resemble early-type galaxies with red continua and strong absorption features, and two objects have spectra reminiscent of starburst (or post-starburst) galaxies.

All of the objects we observed display some evidence of emission lines in their integrated spectra. While the same is true of all of the “normal” galaxies whose spectra are presented by Barger et al. (2001a, 2001b) and Hornschemeier et al. (2001), 19% of the sources classified by Barger et al. (2002) are described as “absorption-line” galaxies. Some of these objects may in fact have faint emission lines — weak [O II] and [O III] emission is visible in the average absorption-line galaxy spectrum shown in Figure 5h of Barger et al. (2002). Others, however, may be devoid of emission features in the data obtained. Two factors are likely to contribute to the relatively high incidence of absorption-line systems in the *Chandra* surveys:

(1) The  $H\alpha$  and [N II] emission lines can be the strongest lines in the spectra of Seyfert galaxies; as such, they are vital for accurate spectroscopic classifications. In fact, the classifications of two of the persistent Seyfert 2s in our sample (Mrk 1066 and MCG +01-27-020) would be ambiguous without information about the lines near  $H\alpha$ . However,  $\sim 70\%$  of the spectra of supposedly normal galaxies published by Barger et al. and Hornschemeier et al. do not cover the  $H\alpha$  region because of the high redshifts of the objects. It is possible that some of the absorption-line galaxies would exhibit emission lines if this region were observed.

(2) Our relatively small sample of nearby objects does not include all possible types of host galaxies. In particular, galaxies with high optical luminosities are absent. Using the expression given in § 12.5 of Barger et al. (2002) and the information listed in Table 1, we find that 14 (78%) of the objects we observed have *B*-band luminosities below  $10^{43}$  ergs s $^{-1}$ , and all have  $L_B < 2 \times 10^{43}$  ergs s $^{-1}$ . In contrast, the majority of the sources spectroscopically classified by Barger et al. have  $L_B$  in excess of  $10^{43}$  ergs s $^{-1}$ . Compared to the objects in our sample, the integrated light of these high- $L_B$  galaxies could more easily overwhelm the emission from moderately luminous Seyfert nuclei. Host-galaxy luminosity may also be related to the detection of optically dull, X-ray-bright objects at fairly low redshifts ( $z < 0.4$ ; see Comastri et al. 2002b). The possibility that some host-galaxy light is excluded in the spectra of these objects is probably offset by the fact that their host galaxies are quite luminous — nine of the ten “normal” galaxies in the Comastri et al. (2002b) study have  $L_B$  greater than a few times  $10^{43}$  ergs s $^{-1}$ .

Thus, as we have speculated previously (Moran et al. 2001), it *is* possible to “hide” the true nature of classical type 2 AGNs in their integrated optical spectra. Low signal-to-noise ratio and inadequate spectral coverage due to redshift effects can hinder the classification process further. We

conclude, therefore, that the demographics of the distant X-ray galaxy population under investigation in deep *Chandra* surveys are more likely to be influenced by the limitations of ground-based spectroscopic observations than by some evolution of the population. The majority of the apparently normal galaxies that have turned up in these surveys, at least those with flat (presumably absorbed) X-ray spectra and/or substantial X-ray luminosities, would probably have optical spectra similar to those of nearby Seyfert 2s if their nuclei could be isolated spatially. If so, this would verify that Seyfert 2 galaxies are the dominant contributors to the hard XRB, as prior research has suggested. Host galaxy dilution is likely to impact any ground-based spectroscopic survey of distant galaxies, leading to underestimates of the numbers of narrow-line AGNs in such surveys.

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## REFERENCES

- [22]Barger, A. J., Cowie, L. L., Mushotzky, R. F., & Richards, E. A. 2001a, *AJ*, 121, 662
- [22]Barger, A. J., et al. 2001b, *AJ*, 122, 2177
- [22]Barger, A. J., et al. 2002, *AJ*, in press
- [22]Comastri, A., et al. 2002b, in “New Visions of the X-ray Universe in the XMM-Newton and Chandra Era,” in press (astro-ph/0203019)
- [22]Comastri, A., et al. 2002a, *ApJ*, 575, 137
- [22]Comastri, A., Setti, G., Zamorani, G. & Hasinger, G. 1995, *A&A*, 296, 1
- [22]Filippenko, A. V. 1982, *PASP*, 94, 715
- [22]Gilli, R., Salvati, M., & Hasinger, G. 2001, *A&A*, 366, 407
- [22]Hornschemeier, A. E., et al. 2001, *ApJ*, 554, 742
- [22]Kennicutt, R. C. 1992a, *ApJ*, 388, 310
- [22]Kennicutt, R. C. 1992b, *ApJS*, 79, 255
- [22]Madau, P., Ghisellini, G., & Fabian, A. C. 1994, *MNRAS*, 270, L17
- [22]Miller, J. S., & Stone, R. P. S. 1993, Lick Observatory Tech. Rep., No. 66
- [22]Moran, E. C., Barth, A. J., Kay, L. E., & Filippenko, A. V. 2000, *ApJ*, 540, L73

- [22]Moran, E. C., Halpern, J. P., & Helfand, D. J. 1996, ApJS, 106, 341
- [22]Moran, E. C., Kay, L. E., Davis, M., Filippenko, A. V., & Barth, A. J. 2001, ApJ, 556, L75
- [22]Mushotzky, R. F., Cowie, L. L., Barger, A. J., & Arnaud, K. A. 2000, Nature, 404, 459
- [22]Schmidt, M., et al. 1998, A&A, 329, 495
- [22]Tozzi, P., et al. 2001, ApJ, 562, 42
- [22]Tully, R. B. 1988, Nearby Galaxies Catalog (Cambridge: Cambridge Univ. Press)
- [22]Ulvestad, J. S., & Wilson, A. S. 1989, ApJ, 343, 659
- [22]Veilleux, S., & Osterbrock, D. E. 1987, ApJS, 63, 295

Table 1. Seyfert 2 Galaxies Observed

Galaxy	$d$ (Mpc) <sup>a</sup>	$m$ <sup>b</sup>	Exp. (s) <sup>c</sup>	Class. <sup>d</sup>
MCG +01-27-020	46.8	14.7	120	Sy2
Mrk 3	54.0	13.6	60	Sy2
Mrk 1066	48.1	13.6	82	Sy2
NGC 262	60.1	13.9	75	Sy2
NGC 591	60.7	13.9	120	Sy2
NGC 788	54.4	13.1	60	N/e
NGC 1358	53.8	12.7	30	N/e
NGC 1667	60.7	13.1	60	N/sb
NGC 1685	60.4	14.5	60	N/e
NGC 2273	28.4	12.3	72	N/e
NGC 3081	32.5	12.8	40	Sy2
NGC 3982	27.2	11.8	36	N/sb
NGC 4117	17.0	14.0	48	N/e
NGC 5283	41.4	14.2	90	Sy2
NGC 5347	36.7	13.2	60	N/e
NGC 5695	56.4	13.8	60	N/e
NGC 5929 <sup>e</sup>	38.5	13.0	40	N/e
NGC 7672	53.5	14.4	86	N/e

<sup>a</sup>Distances from Tully (1988). For the more distant sources ( $cz > 3000 \text{ km s}^{-1}$ ), we assume  $d = cz/H_0$ , where  $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

<sup>b</sup>Optical  $B$  band magnitude, from the NASA Extragalactic Database (NED).

<sup>c</sup>Effective exposure in the scanned observations.

<sup>d</sup>Classification based on the integrated spectrum. Sy2 = Seyfert 2; N/e = normal galaxy with early-type continuum; N/sb = normal galaxy with starburst emission lines.

<sup>e</sup>Interacting with NGC 5930, which is included in the integrated spectrum.



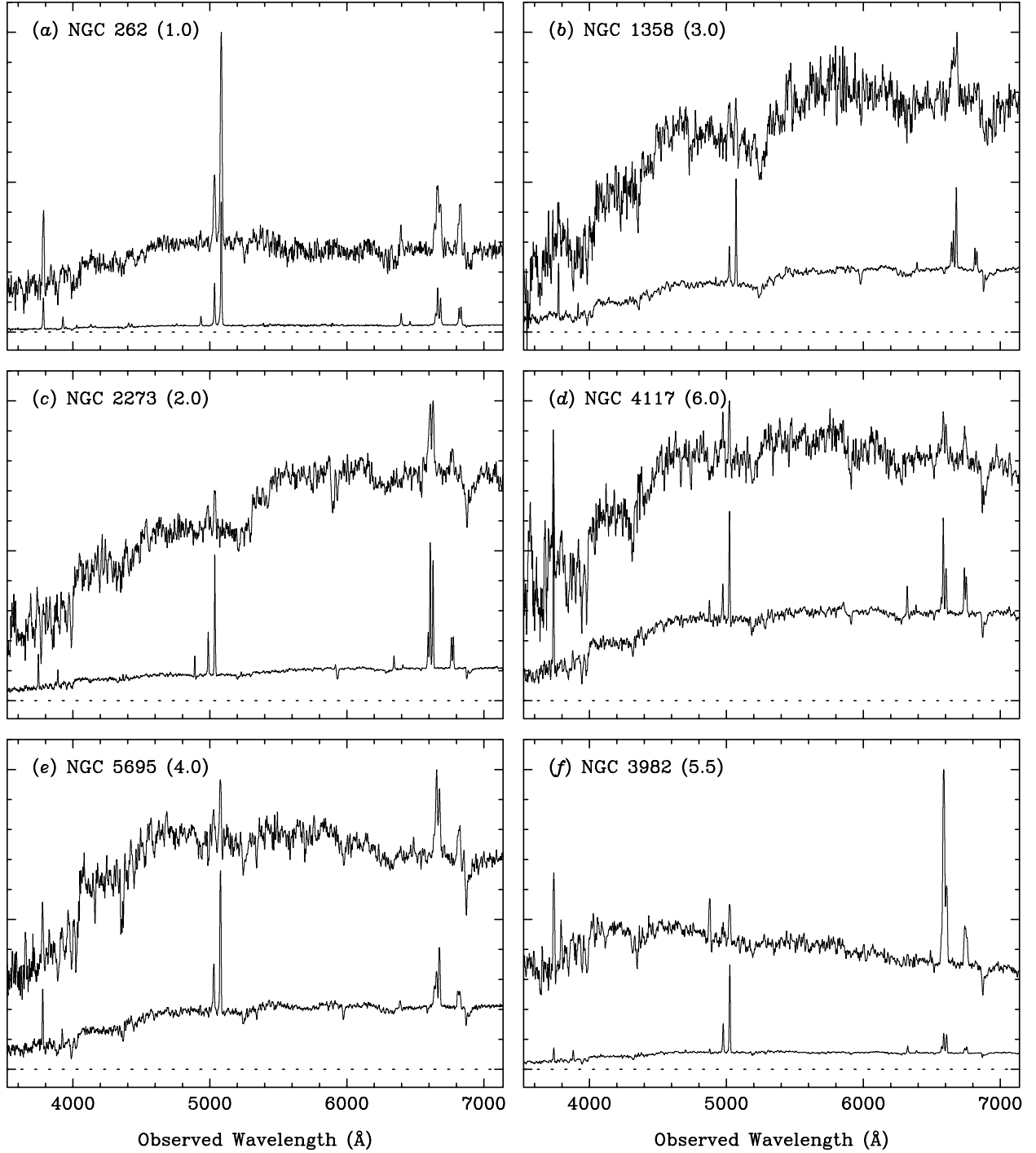


Fig. 1.— Data for six of the observed Seyfert 2 galaxies. Both nuclear (lower trace) and integrated (upper trace) spectra are shown in each panel. Relative flux densities in units of  $\text{ergs cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$  are plotted on the ordinate; the dotted line indicates the zero flux level. For clarity, the nuclear spectrum of each object has been multiplied by a constant, which appears following the galaxy name.